Physics case for low-$\sqrt{s}$ QCD studies at FCC-ee

Based on arXiv:2503.23855 [hep-ex] by D. d'Enterria, P.F. Monni, P. Skands and A. Verbytskyi,
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inspired by Snowmass 2021 contribution

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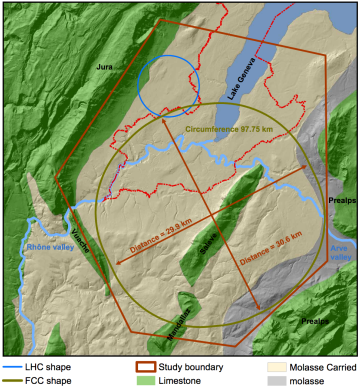
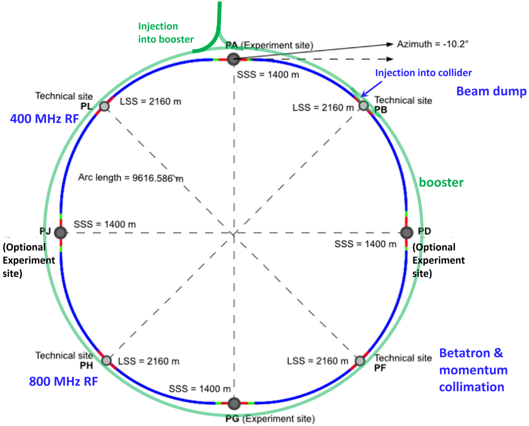
Matter to the Deepest, Katowice, September 14-19th, 2025

FCC-*ee*





Source: Ref. [1, 2].

- e^+e^- collider in CERN, 91 km [3] long, with 4 IPs.
- State of the art detector(s) design.
- Precision goals: 10^{-5} for EW, 10^{-3} for QCD observables.
- A lot of physics [4] **conceptually different from LEP physics**.

QCD tasks for FCC-*ee* era (experimental side)

- **Application of higher& even higher order pQCD and QCD$\times$EW corrections, resummation/showers.**
- Studies of quark mass effects.
- Studies of exotic final states.
- **Better understanding of non-perturbative effects: hadronization, colour reconnection, etc.**.

Those are exactly the areas, which limit the precision of e.g. α_S extraction.

Scales in pQCD, parton showers and non-perturbative corrections

Cross-section for a physical process with hard scale, Q_H, and heavy quark masses m_Q:

$$\mathrm{d}\sigma \;\sim\; \mathrm{Hard}(Q_H, Q, m_Q) \;+\; \mathrm{Resum}(Q_H/Q, Q/m_Q, Q/\Lambda_{\mathrm{QCD}}) \;+\; \mathrm{NonPert}(\Lambda_{\mathrm{QCD}}/Q, m_Q/Q)$$

$\rightarrow$ **Scales matter**.

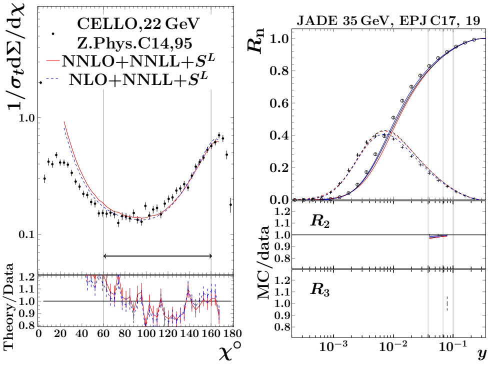
To study

- Non-perturbative effects
- Quark masses
- Parton showers

Exploring the regions with different Λ_{QCD}/Q and m_Q/Q is a must.
Regions with larger Λ_{QCD}/Q and m_Q/Q are preferable for exploration: no reason to avoid the subject of study.

Example: hadronization modeling in $e^+e^- \rightarrow \textit{hadrons}$

- The modern MCEG models are for $\sqrt{s} \approx M_Z$, but not reliable for other energies[5][6] and lower scales.
- This is an artifact: the models were tuned with LEP data at $\sqrt{s} \approx M_Z$ or LHC data, where the tuning does not give very certain results.



- The efforts to re-use the PETRA, TRISTAN and PEP data [7] so far had limited success due to huge data uncertainties.

With enough data away from Z peak, MCEG models can be re-tuned to describe the hadronization better at all energies.

Historically collected data

Accelerator	Energy range, GeV	Luminosity, pb^{-1}	Eligible multihadron events, $\times 10^3$
TRISTAN	$50 - 64$	900 [8]	≈ 110 [9]
PETRA	$12 - 47$	760 [10]	≈ 200 [11, 10]
PEP	29	315 [12]	144 [12]

Table: Estimate of the number of eligible hadronic events at TRISTAN, PETRA, and PEP. The numbers for PETRA were estimated by multiplication of the JADE numbers from Ref. [10] by 4, i.e. assuming the numbers for the MARK-J, TASSO and CELLO experiments are reasonably close. The numbers for TRISTAN were estimated scaling the numbers from Ref. [9] to the total luminosity.

There are even less data available for reanalysis.

An extension of FCC-e^+e^- physics program

Proposed extension of the FCC-e^+e^- program with data taking in range $\sqrt{s} = 40 - 91\,\text{GeV}$

$$\text{FCC-}e^+e^- = \text{Higgs factory} + \text{SuperLEP}$$

$$+ \text{SuperTRISTAN} + \text{SuperPEP} + \text{SuperPETRA}$$

Two **non-exclusive** options are available to get to $\sqrt{s} = 40 - 91\,\text{GeV}$:

- $e^+e^-\gamma$: reduced centre-of-mass energy in radiative events $e^+e^- \to hadrons + \gamma$.
- Dedicated runs: runs with lowered beam energy.

Measurements in focus: event shapes, jets, (heavy flavour) fragmentation functions, hadron multiplicities for MC tunes.

Final questions

- $e^+e^-\gamma$: how good the data are?
- Dedicated runs: how much effort is that?

$e^+e^-\gamma$: yields extrapolated from LEP

Type	$\sqrt{s}'$ (GeV)	$\langle\sqrt{s}'\rangle$ (GeV)	Lumi (pb^{-1})	Selection Eff. (%)	Purity (%)	# Sel. Evts	FCC-ee, estimation
Reduced	30–50	41.4	142.4	48.3	68.4	1247	0.9×10^9
Centre-	50–60	55.3	142.4	41.0	78.0	1047	0.7×10^9
of-	60–70	65.4	142.4	35.2	86.0	1575	1.1×10^9
Mass	70–80	75.7	142.4	29.9	89.0	2938	2.1×10^9
Energy	80–84	82.3	142.4	27.4	90.5	2091	1.5×10^9
	84–86	85.1	142.4	27.5	87.0	1607	1.1×10^9
Z pole	91.2	91.2	8.3	98.5	99.8	248 100	3.1×10^{12}

Table: Properties of the hadronic data samples collected from ISR/FSR by the L3 experiment [13] and estimated number of events that could be similarly obtained at FCC-ee with the expected 100 ab^{-1} at the Z pole.

Better detector technologies (FCC vs. LEP) will not allow for radically larger event yield. The reasons are:

- Better detectors will still have finite resolution, which will be limited by the physics.
- Even for LEP detectors ISR/FSR selection was limited mostly by physics.

$\rightarrow$ LEP selection is a good baseline and extrapolation from LEP makes sense.
5×10^9 events for $\sqrt{s} = 30 - 80\,\text{GeV}$ collected during ≈ 10 years.

$e^+e^-\gamma$: MC studies HOWTO

Processes modeled with Sherpa 3.0.1

- $e^+e^- \to q\bar{q}$
- $e^+e^- \to q\bar{q}\gamma$
- $e^+e^- \to \tau^+\tau^-\gamma$
- $e^+e^- \to \tau^+\tau^-$
- $e^+e^- \to q\bar{q}e^+e^-$
- $e^+e^- \to q\bar{q}\nu\bar{\nu}$
- $e^+e^- \to q\bar{q}\mu^+\mu^-$
- $\gamma\gamma \to$ *hadrons* (several)

and passed through Delphes fast simulation for IDEA detector concept. Output is a subject for selection.

- Approach: select on particle/detector level $\to$ look at composition of selected events.
- Note: selection implies assumptions on the event: event has no ISR/FSR, event has radiation collinear to beam, event has ISR/FSR photon registered in detector.
- Lower-energy dedicated runs are not discussed, as the results are similar to $\sqrt{s} = 91\,\mathrm{GeV}$: close to 100% purity and selection efficiency. Boring!
- The very first observable: mass of HFS

$e^+e^-\gamma$: MC studies selections

Selection

- a) Enough visible hadrons[1] in the final state in the detector acceptance range, requiring that the total visible energy $E_{\rm vis}$ deviates a little from the $2 \times E_{\rm beam}$. In addition, a well isolated high-energy[2] photon with energy E_γ is registered in the detector. The HFS without the photon is clustered into two jets which should satisfy the triangle condition, see Eq.3 in Ref. [?] for details[3]. This selection aims to select wide-angle high-energy FSR/ISR events and reconstruct the kinematics of these events correctly.
- b) Enough visible hadrons in the final state in the detector acceptance range, requiring that the total visible energy E_{vis} deviates a little from the $2 \times E_{\rm beam} - |P_{\rm vis,z}|$, where $P_{\rm vis,z}$ is the longitudinal component of the total visible momenta. The later condition implies an existence of a single ISR photon radiated parallel to the beam and not registered in the detector, which is almost completely responsible for the momenta imbalance in the event [4]. The events should also fail the criterion a). This selection is designed to select events with FSR/ISR photons collinear to the beam direction and reconstruct the kinematics of these events correctly.
- c) Enough visible hadrons in the final state in the detector acceptance range, requiring that the total visible energy $E_{\rm vis}$ deviates a little[5] from the $2 \times E_{\rm beam}$, and that the thrust vector direction is contained within the detector acceptance range[6]. The events should also fail the criterion a). This selection is aimed at selecting events without significant FSR/ISR and reconstruct the kinematics of these events correctly.

[1] at least five tracks or calorimeter objects

[2] at least 10 GeV

[3] The photon energy can be also estimated clustering the remaining HFS into two jets j_1 and j_2 and using from the sinus theorem

$$E_{\gamma,triangle} = 2 \times E_{beam} \times \frac{|\sin j_1 \wedge j_2|}{|\sin j_1 \wedge j_2| + |\sin j_1 \wedge \gamma| + |\sin j_2 \wedge \gamma|.}$$

E_γ should lie in the $[E_{\gamma,triangle} - 10GeV, E_{\gamma,triangle} + 5GeV]$ interval. The photon should be isolated from the jets such that $min(j_1 \wedge \gamma, j_2 \wedge \gamma) > 0.5$.

[4] Therefore the requirement ($\vec{P}_{\rm vis} \wedge beam < 3^\circ$ or $\vec{P}_{\rm vis} \wedge beam > 177^\circ$) is imposed.

[5] less than 5 GeV

[6] $|\cos\theta_T| < 0.9$

$e^+e^-\gamma$: MC studies results

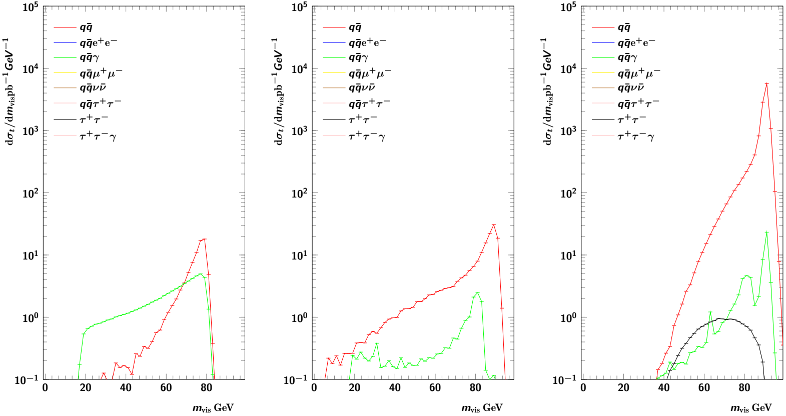


Figure: Distribution of the invariant mass of the visible HFS for the events that passed the selection criteria. The photon is excluded from the HFS mass calculation. All the final states but $q\bar{q}$, $q\bar{q}\gamma$ and $\tau^+\tau^-$ are strongly suppressed by the selection requirements. The full visible signal in the detector will be the sum of the displayed processes. Left: Event passed selection ***a***. The selection assumptions on kinematics are correct for $q\bar{q}\gamma$ "signal" samples. Center: Event passed selection ***b***. The selection assumptions on kinematics are correct for $q\bar{q}$ "signal" samples with collinear radiation. Right: Event passed selection ***c***. The selection assumptions on the kinematics are correct for $q\bar{q}$ "signal" samples with negligible radiation.

$e^+e^-\gamma$: MC studies results

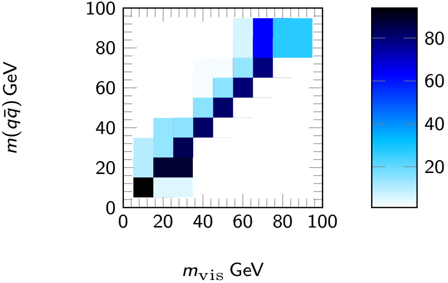


Figure: Correlation of the $m(q\bar{q})$ and the mass of the HFS on the detector level for the $\mathrm{e^+e^-} \to \mathrm{hadrons} + \gamma_{FSR}$ events passed selection *a* The values are normalized across the x axis and the colour coding scale is given in %.

The “resolution” is a couple of GeV $\to$ bin size for combination of events should be of the same order, e.g. $5GeV$.

$e^+e^-\gamma$: MC studies conclusions

- More or less the purity and the accessible range of centre-of-mass energy is restricted by physics even with the state-of-the art detectors.
- With tight selection and enough statistics one can get reasonably large and pure event samples in the region $\sqrt{s} = 20 - 60\,\mathrm{GeV}$.
- MC studies are ongoing: more backgrounds, higher statistics, etc.

Dedicated runs: machine parameters

- The work on the feasibility of machine settings is ongoing.
- Calculations kindly provided by Katsunobu Oide for $\sqrt{s} = 40, 60\,GeV$.
- Also: lower requirements for beam energy spread, beam energy, etc.

FCC-ee collider parameters for Z and $E_{\rm beam} = 30\,$GeV, Nov. 28, 2024.
SR: symchrotron ratioation, IB: +intrabeam scattering, BS: +beamstrahlung

Beam energy	[GeV]	45.6	30	20
Layout		PA31-3.0		
# of IPs		4		
Circumference	[km]	90.658728		
Bend. radius of arc dipole	[km]	10.021		
Energy loss / turn	[GeV]	0.0390	0.0072	0.0014
SR power / beam	[MW]	50	9.3	1.8
Beam current	[mA]	1294		
Colliding bunches / beam		11200	60000	60000
Colliding bunch population	[10^{11}]	2.18	0.407	0.407
Hor. emittance at collision ε_x	[nm]	0.70	0.48	0.86
Ver. emittance at collision ε_y	[pm]	2.3	0.98	1.71
Lattice hor. emit. $\varepsilon_{x,\rm lattice}$ (SR/IB/BS)	[pm]	1.05 / - / -	0.31 / 0.54 / 0.48	0.14 / 0.93 / 0.86
Lattice ver. emittance $\varepsilon_{y,\rm lattice}$	[pm]	1.05	0.53	1.06
Arc cell		Long 90/90		
Momentum compaction α_p	[10^{-6}]	28.66		
Arc sext families		75		
$\beta^*_{x/y}$	[mm]	130 / 0.7		
Transverse tunes $Q_{x/y}$		218.145 / 222.220		
Chromaticities $Q'_{x/y}$		+2 / +5		
Energy spread (SR/IB/BS) σ_δ	[%]	0.039 / - / 0.121	0.026 / 0.032 / 0.061	0.017 / 0.046 / 0.0598
Bunch length (SR/IB/BS) σ_z	[mm]	4.70 / - / 14.6	2.4 / 3.0 / 5.8	1.9 / 5.1 / 6.6
RF voltage 400/800 MHz	[GV]	0.103 / 0		0.05
Harm. number for 400 MHz		121200		
RF frequency (400 MHz)	MHz	400.787129		
Synchrotron tune Q_s		0.0340	0.0436	0.0371
Long. damping time	[turns]	1181	4140	14000
RF acceptance	[%]	1.41	2.36	2.09
Energy acceptance (DA)	[%]	±1.0		
Beam crossing angle at IP θ_x	[mrad]	±15		
Crab waist ratio	[%]	50		
Beam-beam ξ_x/ξ_y [a]		0.0032 / 0.1009	0.0054 / 0.1010	0.0061 / 0.1052
Piwinski angle $(\theta_x \sigma_{z,\rm BS})/\sigma^*_x$		22.3	10.9	9.4
Lifetime (q + BS + lattice)	[sec]	10900	61000	59000
Lifetime (Touschek)	[sec]	-	6100	7100
Lifetime (lum) [b]	[sec]	1320	1930	3100
Luminosity / IP	[10^{34}/cm^{2}s]	145	102	65

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section, no beam size effect.

Dedicated runs: timescale

$\sqrt{s}$ (GeV)	Time (days) to collect 10^9 hadronic events $\mathcal{L} \propto \sqrt{s}$
80	7
70	17
60	22
50	22
40	18

Table: Time needed to collect 10^9 hadronic events in dedicated runs at given CM energy assuming instant luminosity $\mathcal{L}$ is the same as at Z peak and is equal to 4.6 $pb^{-1}s^{-1}$ or alternatively assuming the scaling $\mathcal{L} \propto \sqrt{s}$ [14].

We are discussing weeks of datataking.

Dedicated runs: conclusions

- Estimation of time to change energy by the accelerator experts is 1 week.
- $\rightarrow$ 10 points will take 3 months just to switch the energies is **a luxury**.

$\rightarrow$ A more humble, but still extendable suggestion: **two runs at 40 GeV and 60 GeV**. Total runtime: 6-8 weeks. Preferably **in the first year of running** to be able to use results for MC tunes, calibration, etc of further analyses.

$e^+e^-\gamma$ vs. dedicated runs: historical evidence

Clear differences between the precision of results with e.g. α_s extraction.
OPAL [15]:

$0.1182 \pm 0.0015(\mathrm{stat.}) \pm 0.0038(\mathrm{exp.syst.}) \pm 0.0070(\mathrm{hadr.}) \pm 0.0062(\mathrm{theory.})(NLO)$

vs JADE [16]:

$0.1172 \pm 0.0006(\mathrm{stat.}) \pm 0.0020(\mathrm{exp.syst.}) \pm 0.0035(\mathrm{hadr.}) \pm 0.0030(\mathrm{theory.})(NNLO + NLLA)$

	Year	Type	$\sqrt{s}$	Hadr. unc.	Exp. syst. unc .
JADE	2008	Low energy run	12-46	0.0035	0.0020
OPAL	2007	$e^+e^-\gamma$	10-45	0.0070	0.0038

$e^+e^-\gamma$ vs. dedicated runs: costs and personpower

	Dedicated runs	$e^+e^-\gamma$
Detector amendments.	=0€ extra for detector construction	In base program
Running time for dedicated runs would be some weeks with lower energy consumption.	≈?€ extra for running	In base program
The changes of beam energies would require readjustments of some magnets (but not the main ring).	Some manpower and time (a week?)	Not needed.
The data is of same type as the data at and above Z and would fit into any software/analysis for higher energy.	≈0€ extra for computing and physics	In base program
Data availability	In some months	After 10 years.

Costs in terms of money, time and personpower expected to be tiny, but should be evaluated more carefully.

$e^+e^-\gamma$ vs. dedicated runs: measurements of QCD observables

$e^+e^-\gamma$

- Measure γ energy.
- Calculate the CM boost assuming γ comes from ISR/FSR.
- Alternatively to the points above do a kinematic fit of the hadronic final state to gen the energy of γ.
- Boost the event to the calculated CM.
- Calculate observables from the boosted hadronic final state.

Dedicated runs

- Make sure the CM energy is close to nominal using cuts.
- Calculate observables from hadronic final state.

The measurement of γ and the boost procedure bring additional uncertainties. The performance of these methods could be insufficient for the desired accuracy of the measurements.

Conclusions

- The feasibility studies for the low-energy runs at FCC-*ee* are in a well developed state, feedback from accelerator experts, MC studies, etc. The contribution to European Strategy was made.
- The current proposal, which takes into account the time constraints and machine capabilities is to have two runs at $\sqrt{s} = 40\,\text{GeV}$ and $\sqrt{s} = 60\,\text{GeV}$ to collect 10^9 per run and complement those data with the data from ISR/FSR events. In case of the imminent success those data taking options can be extended with more energy points and/or higher statistics.

Thanks to

Andrea Banfi, Sigfried Bethke, Alain Blondel, Patrick Janot, Adam Kardos, Stefan Kluth, Bogdan Malaescu, Katsunobu Oide, Gábor Somogyi, Zoltán Szőr, Zoltán Trócsányi, Zoltán Tulipánt, Giulia Zanderighi

Open questions

- Q: How good are the $e^+e^-\gamma$ for measurements of particular observables?
- A: Studies are ongoing for jets/event shapes, but the results are expected to be close to those form m_{vis} .

Backups and discussion

$e^+e^-\gamma$ vs. dedicated runs

- There will be enough data from $e^+e^-\gamma$ anyway.
- Not really and not of good quality, see L3 [17] and OPAL [15] at LEPI:

Type	$\sqrt{s}$, GeV	$\langle\sqrt{s}\rangle$, GeV	Int. Lumi (pb)	Selection Eff.(%)	Purity(%)	Sel. Events
Reduced	30–50	41.4	142.4	48.3	68.4	1247
Centre-	50–60	55.3	142.4	41.0	78.0	1047
of-	60–70	65.4	142.4	35.2	86.0	1575
Mass	70–80	75.7	142.4	29.9	89.0	2938
Energy	80–84	82.3	142.4	27.4	90.5	2091
	84–86	85.1	142.4	27.5	87.0	1607
Z pole	91.2	91.2	8.3	98.5	99.8	248100

$\alpha_S(M_Z)_{41\text{ GeV}} = 0.1418 \pm 0.0053(\text{stat.}) \pm 0.0030(\text{exp.syst.}) \pm 0.0055(\text{hadr.}) \pm 0.0085(\text{theory.})(NLO)$
$\alpha_S(M_Z)_{55\text{ GeV}} = 0.1260 \pm 0.0047(\text{stat.}) \pm 0.0056(\text{exp.syst.}) \pm 0.0066(\text{hadr.}) \pm 0.0062(\text{theory.})(NLO)$
...V.S.
$\alpha_S(M_Z)_{91\text{ GeV}} = 0.1210 \pm 0.0008(\text{stat.}) \pm 0.0017(\text{exp.syst.}) \pm 0.0040(\text{hadr.}) \pm 0.0052(\text{theory.})(NLO)$

E_γ [GeV]	Events	$\sqrt{s'}_{Mean}$[GeV]	Background [%]		
			Non-rad. MH		$\tau\tau$
			Likelihood	Isolated tracks	
10-15	1560	78.1± 1.7	6.0± 0.7	6.2± 0.9	0.9± 0.2
15-20	954	71.8± 1.9	3.1± 0.5	4.9± 0.8	1.0± 0.3
20-25	697	65.1± 2.0	2.6± 0.6	6.3± 1.1	0.9± 0.4
25-30	513	57.6± 2.3	5.1± 1.1	7.9± 1.4	1.1± 0.5
30-35	453	49.0± 2.6	4.5± 1.1	9.6± 1.6	0.7± 0.4
35-40	376	38.5± 3.5	5.2± 1.2	13.1± 1.9	0.8± 0.5
40-45	290	24.4± 5.3	10.4± 2.3	12.9± 1.7	0.8± 0.5

$\alpha_S(M_Z)_{comb} = 0.1182 \pm 0.0015(\text{stat.}) \pm 0.0038(\text{exp.syst.}) \pm 0.0070(\text{hadr.}) \pm 0.0062(\text{theory.})(NLO)$

+specific problems: hadronization, systematics, statistics.

Results from $e^+e^- \to hadrons$

Determination[7]	Type	Data and procedure	Ref.
0.1175 ± 0.0025	Non-global	ALEPH 3-jet rate (NNLO+MChad)	[19]
0.1199 ± 0.0059	fit	JADE 3-jet rate (NNLO+NLL+MChad)	[20]
0.1224 ± 0.0039	+MChad	ALEPH event shapes (NNLO+NLL+MChad)	[21]
0.1172 ± 0.0051		JADE event shapes (NNLO+NLL+MChad)	[16]
0.1189 ± 0.0041		OPAL event shapes (NNLO+NLL+MChad)	[22]
$0.1164\ ^{+0.0028}_{-0.0026}$	Global fit	Thrust (NNLO+NLL+anlhad)	[23]
$0.1134\ ^{+0.0031}_{-0.0025}$	+anlhad	Thrust (NNLO+NNLL+anlhad)	[24]
0.1135 ± 0.0011		Thrust (SCET NNLO+N^{3}LL+anlhad)	[25]
0.1123 ± 0.0015		C-parameter (SCET NNLO+N^{3}LL+anlhad)	[26]
0.11750 ± 0.00287	Global fit	EEC (NNLO+N^{2}LL+MChad+NLO$_{m_b}$)	[6]
0.11881 ± 0.00131	+MChad	2-jet rate (N^{3}LO+N^{3}LL+MChad+N^{2}LO$_{m_b}$)	[5]

Global fits and wide $\sqrt{s}$ range $\to$ best precision.
The discrepancy between the analytic and MC hadronization should be clarified.

[7] Credits to Ref. [18]

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